MISSION ORBIT BASED ON SCIENCE REQUIREMENTS FOR THE RADIATION BELT STORM PROBES (RBSP) MISSION

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JULY 9, 2007

Abstract

It has been determined that the following orbital parameters offer the optimal configuration required for the RBSP mission to meet its science goals:

Priority 1	**Perigee**	**Apogee**	**Inclination**
Spacecraft A	600 km, altitude	5.5 Earth Radii (R_E) geocentric distance	6°, geographic latitude
Spacecraft B	600 km, altitude	5.8 R_E geocentric distance	6°, geographic latitude

If the recommended inclination or separation in apogees cannot be obtained within the RBSP resource constraints, the following sets of orbit parameters, in priority order, meet the science objectives and are acceptable, although with increasingly compromised science return.

Priority 2	**Perigee**	**Apogee**	**Inclination**
Spacecraft A	600 km, altitude	5.5 R_E geocentric distance	10°, geographic latitude
Spacecraft B	600 km, altitude	5.8 R_E geocentric distance	10°, geographic latitude

Priority 3	**Perigee**	**Apogee**	**Inclination**
Spacecraft A	600 km, altitude	5.8 R_E geocentric distance	6°, geographic latitude
Spacecraft B	600 km, altitude	5.8 R_E geocentric distance	6°, geographic latitude

Priority 4	**Perigee**	**Apogee**	**Inclination**
Spacecraft A	600 km, altitude	5.8 R_E geocentric distance	10°, geographic latitude
Spacecraft B	600 km, altitude	5.8 R_E geocentric distance	10°, geographic latitude

The intent is to significantly reduce science implementation risk by providing optimal radial coverage of important particle acceleration events, while also enabling azimuthal coverage of wave phenomena with time.

If the apogees of the two spacecraft cannot be separated by the amounts recommended, the RBSP science team recommends investigating the possibility of separating the perigees of the two spacecraft to increase the differential precession of the spacecraft lines of apsides to approximately 30° per year.

Introduction

The scientific goal of the G-RBSP mission is to understand, ideally to the point of predictability, how populations of relativistic electrons and ions in space form or change in response to variable inputs of energy from the Sun. This goal can be accomplished via the analysis of extensive observations within the Earth's inner magnetosphere, including its radiation belts. To guide the observations and analysis, the G-RBSP mission has defined 8 prioritized objectives which include: identifying the processes that energize, transport, and cause the loss of relativistic and near-relativistic particle populations; quantifying the processes that cause the formation of transient radiation belt structures; distinguishing between and quantifying adiabatic and non-adiabatic processes that operate upon the particle populations; determining the role of source populations; quantifying the effects of the ring current on the particle population; determining how and why the ring current varies; and constructing models for the radiation belts.

Previous missions to the Earth's radiation belts employed only a single spacecraft. Although these missions provided considerable information concerning radiation belt processes, they were not able to distinguish between spatial and temporal phenomena unambiguously, determine the instantaneous spatial extent of phenomena, nor simultaneously measure source and energized particle populations. In particular, single spacecraft measurements cannot distinguish between different mechanisms for generating particles with relativistic and near-relativistic energies. Doing so requires calculating the radial gradient in the phase space density from radially-separated measurements of energetic particle pitch angle distributions relative to the magnetic field at locations at or very close to the geomagnetic equator. In addition to the advanced instrumentation to be employed, the important new aspects of the G-RBSP mission lie in its ability to make simultaneous measurements of the plasma, energetic particles, magnetic and electric fields, and wave observations at two separate locations, or at the different times at the same location.

The Geospace Mission Definition Team (GMDT) report recommended that the two G-RBSP spacecraft lie in near-equatorial orbits with 5.5 R_E geocentric apogees. An apogee of 5.5 R_E geocentric radial distance was recommended as ideal because it lies between the location of the peak energy fluxes (but not the location of the most variable phase space density) in the radiation belts near 4 R_E geocentric radial distance and geosynchronous orbit at 6.6 R_E where GOES and LANL spacecraft provide good coverage of the outer boundary of the Earth's radiation belts. The 5.5 R_E orbit has a period near 9 hours. The reasons given for an orbit near the magnetic equator were: '(1) to obtain the full equatorial pitch angle distribution, including 90° mirroring particles, (2) to simplify calculation of phase space densities at fixed adiabatic invariants, (3) to avoid errors inherent in the use of magnetic field models when mapping of off-equatorial distributions to the equator, and (4) to capture wave fields that can be strongly confined to the near-equatorial region'. The GMDT report stated that there was 'only marginal value in bringing the inclination below 10° because the near-equatorial coverage does not increase'.

Presentations made by the RBSP Project Science Team following completion of the GMDT report stated that the planned orbit had a 500 km altitude perigee, 5.5 R_E geocentric distance apogee and $\leq$18° (12° goal) geographic inclination. However, the appendix to the GMDT report provided a study of spacecraft in chasing orbits with a perigee at 500 km altitude, an apogee at 5.8 R_E geocentric distance, and a geographic inclination of $\leq$18° (12° goal). Based on inputs from the Project team, the subsequent Radiation Belt Storm Probes Investigations and Geospace-Related Missions of Opportunity Announcement of Opportunity (AO) specified a 500 km x 5.8 R_E orbit and $\leq$18° inclination. Furthermore, the AO stated that a small dV between the two spacecraft at deployment would suffice for one spacecraft to lap the other several times during the mission and result in nearly identical orbits that slowly drift apart. Significant spacecraft apogee separations were not recommended because they were thought to require additional investments in the spacecraft bus, while the inclination was bounded by the capabilities of the expected Delta II launch vehicle available at the time.

Since the time of the selection, the need to baseline a larger launch vehicle (Atlas V or Delta IV) than would otherwise have been required has enabled spacecraft orbit scenarios heretofore not thought possible within mission resource constraints. A reexamination of the orbits affords an opportunity to reconsider the apogee(s) recommended by the GMDT, stated in the AO, and currently baselined by the mission. The RBSP Project Scientist, in consultation with the RBSP Science Working Group (SWG), was asked to review the orbit apogee and inclination and, within the context of the increased launch vehicle capabilities, to recommend an optimal orbit that will maximize the science return of the mission.

Analysis

There have been ongoing discussions and analysis of the orbit best suited for the scientific objectives of the G-RBSP mission since the time when the instruments were selected. During the months of May and June 2007, a tiger team formed to establish quantitative criteria for identifying scientifically optimal orbits. The team considered two inclinations (i = 6 and 10°) and spacecraft apogees ranging from 5.2 to 5.8 R_E geocentric radial distance, including scenarios in which the two spacecraft have different apogees.

The tiger team, composed of RBSP project personnel, SWG group members and/or designees with experience in all the major aspects of radiation belt studies, identified the probable spatial extent of phenomena relevant to the G-RBSP mission, including particle source regions, the region where the radiation belt fluxes peak, zones of ULF and VLF wave activity, and regions where substorm plasma injections are likely. Phenomena not requiring orbit optimization were not considered.

For each potential orbit scenario, the team calculated the probability of one or both spacecraft passing at least twice during the course of a two-year mission through each region of interest when a radiation belt event was in progress. A high probability of at least one spacecraft observing a given phenomena at least twice during the mission was interpreted as the minimum required to meet full mission success. Weightings based on the RBSP science priorities were not applied to this analysis.

The tiger team performed other tests, including a “back-to-back revisit” test, in which the two spacecraft should revisit a given region of interest within two hours, and a “simultaneous observation” test, in which the two spacecraft would simultaneously observe different processes relevant to particle acceleration, transport, or loss.

This new analysis was combined with other studies performed over the past nine months and used to form the recommendations below. The additional work includes histograms of spacecraft dwell times and comparisons to phase space density variations observed on previous spacecraft missions.

Findings:

1. Orbital Inclination**: Orbits with inclinations of 6° are preferable to those with inclinations of 10° for all phenomena considered with the exception of dayside chorus waves.**

The primary benefit of orbits with the lower inclination lies in the fact that the spacecraft spends more time in the vicinity of the geomagnetic equator, where the full particle pitch angle distributions can be resolved; these distributions are needed to accurately determine radial gradients in phase space densities and thereby discriminate between proposed models for particle energization, transport, and loss: one of the central objectives of the G-RBSP mission.

Particles with pitch angles near 90° remain trapped in the vicinity of the magnetic equator and cannot be observed at off-equatorial locations. If it were the case that particle fluxes varied smoothly with pitch angle, unobserved fluxes of equatorially-mirroring particles might be inferred by extrapolating off-equatorial measurements at lower pitch angles. However, as illustrated in Figure 1, wave-particle interactions frequently result in pitch angle distributions in which the flux varies abruptly with pitch angle.

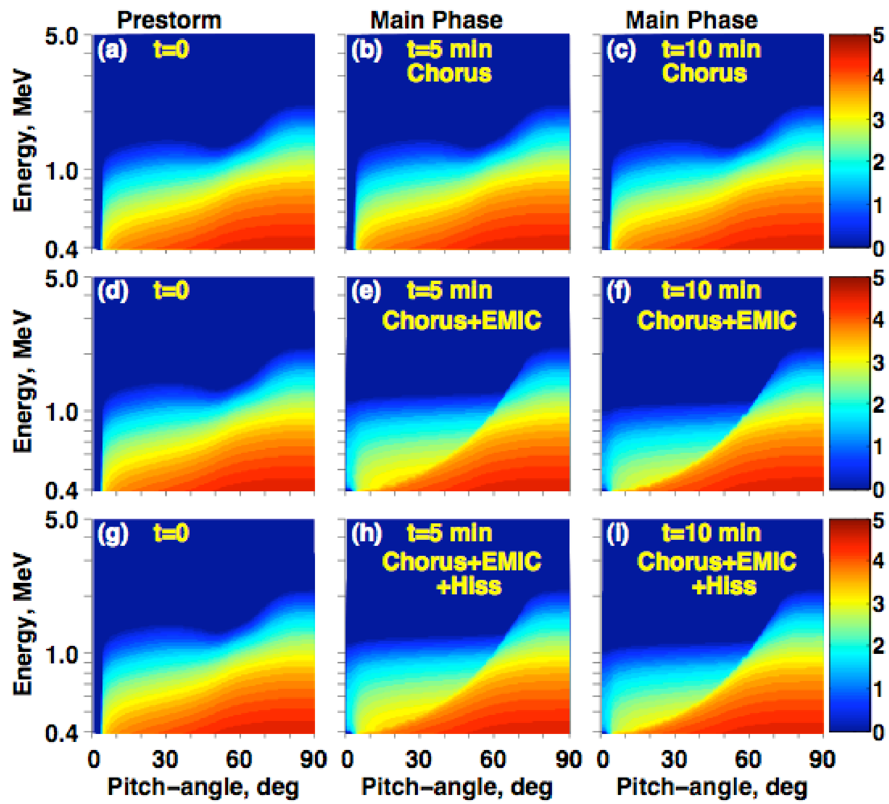

Figure 1. When wave-particle interactions (chorus, EMIC, hiss) are included in 2-D models for energy and pitch-angle diffusion of energetic particles within the Earth's radiation belts, equatorial pitch angle distributions develop strong gradients in flux versus pitch angle. Since particles with large pitch angles cannot be observed far from the geomagnetic equator, there is a danger that off-equatorial spacecraft located will miss the sharp gradients and that important information concerning the processes operating within the radiation belts will be lost. To infer the existence of a gradient in the fluxes of 0.4 to 1 MeV electrons, observations must be made to pitch angle of at least 60°. This figure provided courtesy of Richard Thorne and Wen Li.

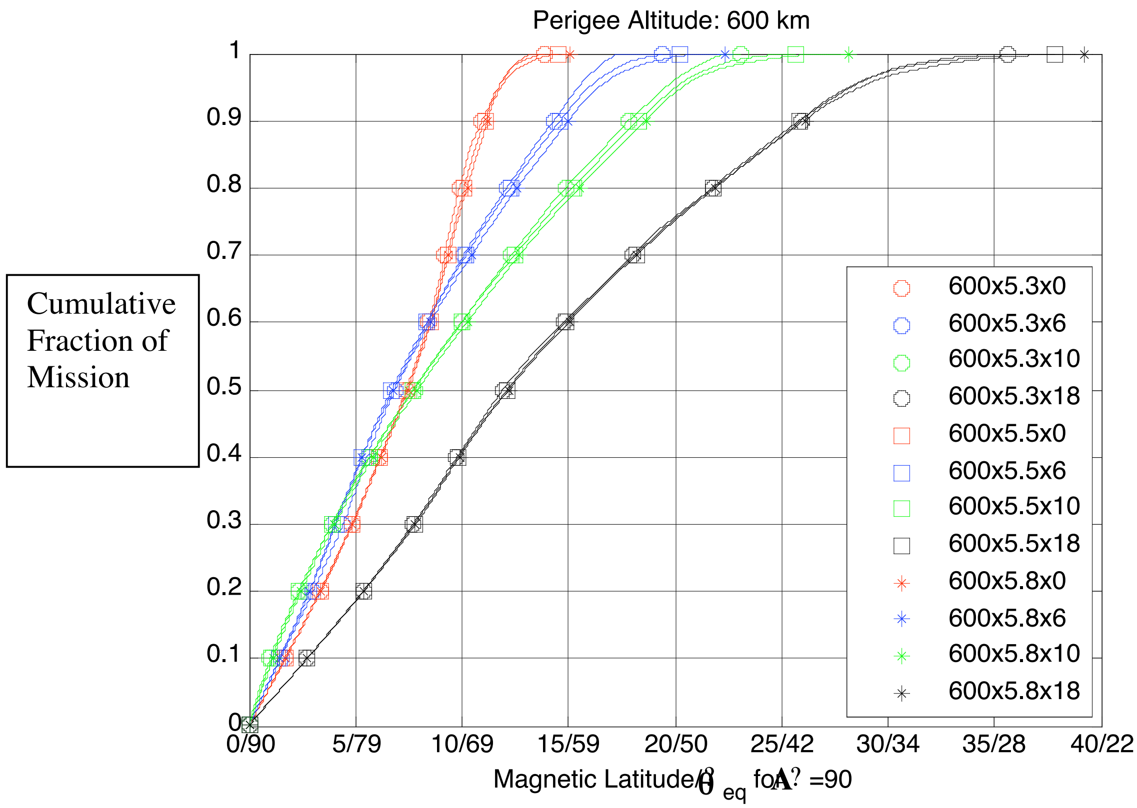

Figure 2. The normalized cumulative distribution of magnetic latitudes covered by missions with perigees of 600 km altitude, 5.3 to 5.8 Earth radii (RE) geocentric distance apogees, and geographic inclinations ranging from 0 to 18°. The argument of perigee (A) is 90°. The double values on the horizontal axis indicate the magnetic latitude/equatorial pitch angle (θ), while the vertical axis indicates the cumulative percentage of the mission spent at or below each latitude (or, alternatively, with equatorial pitch angle coverage up to the value shown). A decrease in the inclination from 10 (green) to 6° (blue) results in an increase in the fraction of the mission during which particles with pitch angles less than 60° can be observed from 80 to 90%. This figure provided courtesy of Paul O'Brien.

The sharpest gradients in 0.4 to 1 MeV electron flux versus pitch angle seen in Figure 1 occur at pitch angles ranging from 30 to 60°. Taking the latter value as the cut-off value for the minimum pitch angle that must be observed in order to understand the nature of the equatorial particle pitch angle distributions, calculate, and compare phase space densities at the two spacecraft, then Figure 2 indicates that a decrease in the orbital inclination from 10° to 6° increases the fraction of data usable for these purposes from 80 to 90% during the course of a two-year mission. The fraction of usable data diminishes steadily as inclinations increase beyond 10°.

To study the time history of events within the Earth's radiation belts, it is important to observe phase space densities on sequential passes through the radiation belts. Geomagnetic storms typically last 3 days. With apogees near 5.8 R_E, the G-RBSP spacecraft will make 16 passes on 8 orbits through the radiation belts during the course of a typical storm. Figure 3 tracks the magnetic latitude and maximum equatorial pitch angle observable on 8 successive orbits for two inclinations (6 and 10°) and two extremes in the instantaneous arguments of perigee (0 and 90°). Inspection reveals that a reduction in the inclination from 10 to 6° increases the number of passes through the 4 to 5.5 L* range with pitch angle coverage to angles greater than 60° from 13.5 to 15 when the argument of perigee (AOP) is 0° and from 10 to 13.5 when the AOP is 90°. From this we conclude that a reduction in the inclination of the orbit significantly improves opportunities to track radial phase space density profiles during the course of geomagnetic storms.

Optimizing measurements of the full energetic particle distribution has always been a high-priority goal of the RBSP mission. However, achieving this goal this comes at the expense of coverage of off-equatorial phenomena, in particular waves. With a 6° inclination RBSP may often miss such waves, perhaps resulting in an underestimation of their occurrence and significance to the physics under study, and certainly resulting in a reduction of our ability to determine their latitudinal structure.

Of particular interest here are lower-band chorus emissions [Meredith et al., GRL, 30, doi:10.1029/2003GL017698, 2003]. As can be seen in the left panel of Figure 4, from evening to dawn the most intense of these emissions occur beyond L =3 confined to a region within 15° of the geomagnetic equator. By contrast, from dawn to afternoon intense emissions extend beyond geomagnetic latitudes of 30° (middle panel). From afternoon to evening emissions are generally weak or absent (right panel). By decreasing the inclination of the G-RBSP mission 10 to 6°, observations of emissions from 17° to 21° would be lost. However, there is no obvious break or change in emissions within this latitude range requiring observation, indicating that it should be possible to infer the occurrence of the waves from measurements at low-latitudes. It must also be noted that orbits with 6° inclinations enhance coverage of other wave fields that lie trapped in the vicinity of the equator, e.g. equatorial trapped noise, as shown in Figure 5 [Santolik et al., Ann. Geophys., 22, 2587, 2004].

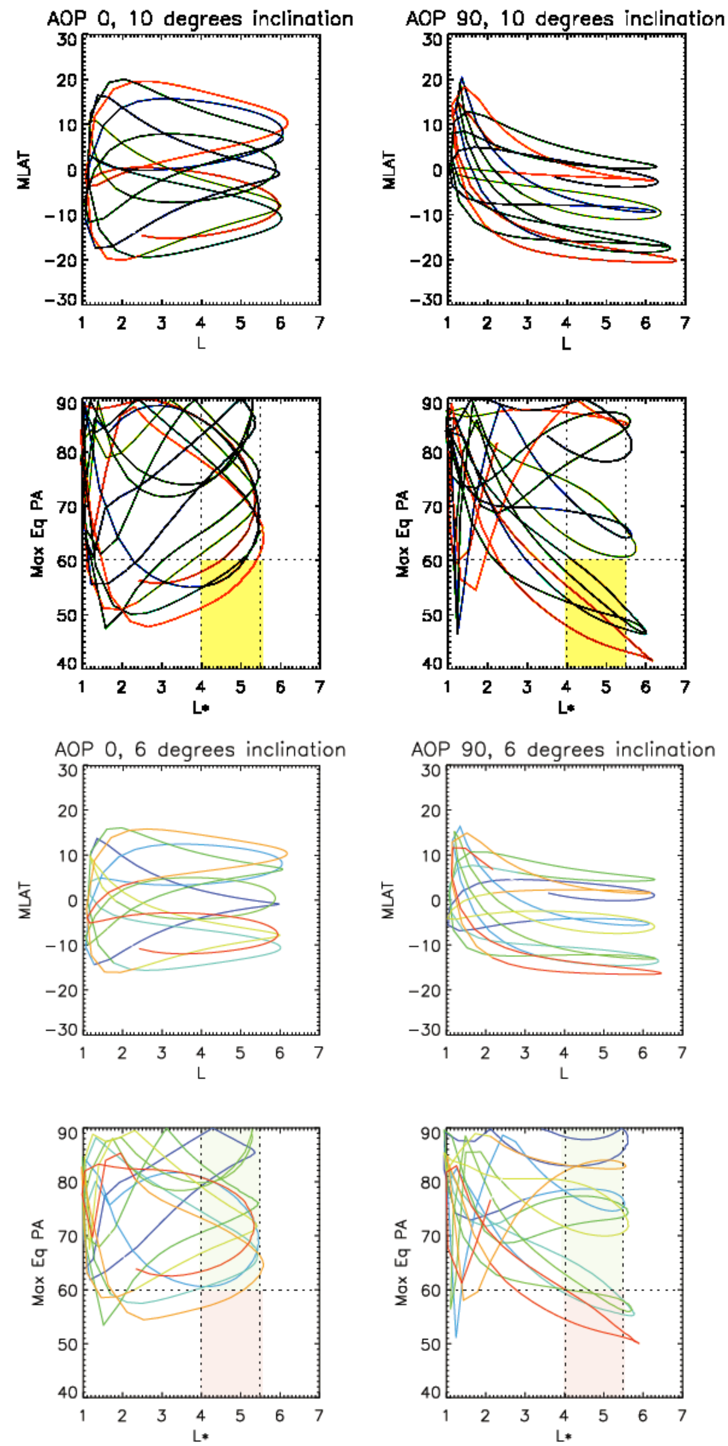

Figure 3. The magnetic latitudes and equatorial pitch angles covered by spacecraft in orbits with 5.8 R_E apogees, 600 km perigees, and 10° (upper four panels) or 6° (lower four panels) inclinations. The left column shows results for 0° instantaneous arguments of perigee (AOP), while the right panel shows results for 90° AOP. Vertical dashed lines focus attention on the region from L* = 4 to 5.5, while a horizontal dashed line indicates the 60° pitch angle cut off discussed in the text.

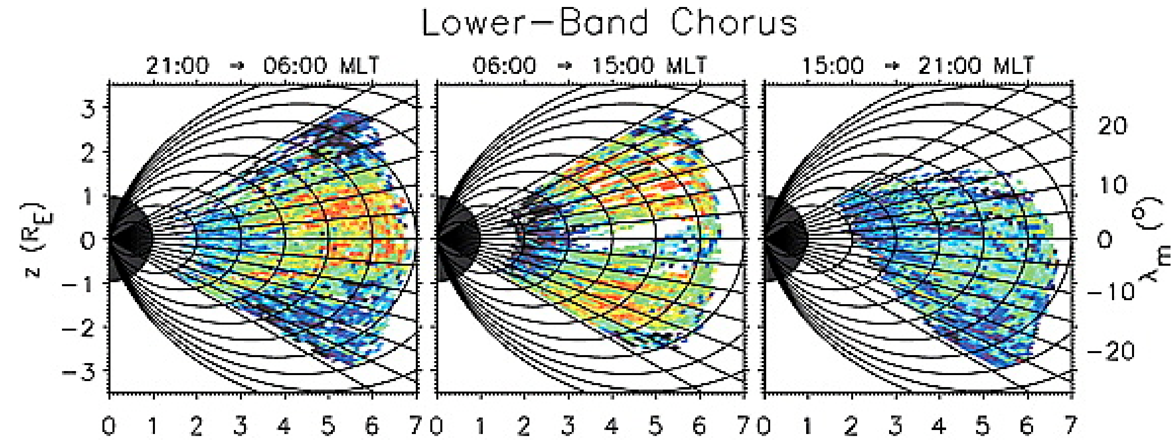

Figure 4. Lower band ($0.1 < f/f_{ce} < 0.5$) chorus magnetic field intensities for three different local time sectors during active conditions as a function of radial distance from the Earth in x-y plane and z. The intensities observed by CRRES are portrayed on a log scale with red corresponding to 10^4 pT^2 and blue to 1 pT^2. Dipole field lines and lines of constant geomagnetic latitude from the Olson-Pfitzer tilt-dependent static model have been superimposed [Meredith et al. 2003].

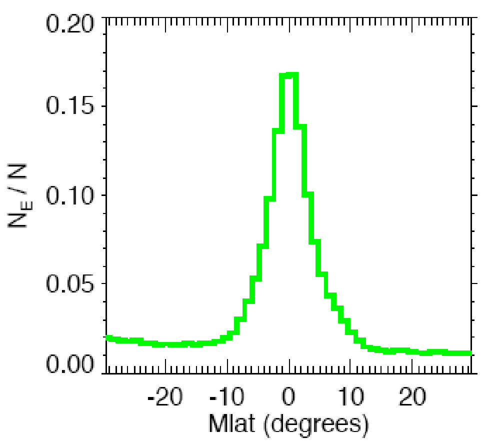

Figure 5. Cluster observations of the probability of observing equatorial noise as a function of dipole magnetic latitude [Santolik et al., 2004].

Furthermore, it is important to note that wave-particle interactions occur over a wide range of magnetic latitudes. When measurements are made at low-latitudes, some information concerning waves at high latitudes may be lost. However, it is equally true that when measurements are made at high latitudes, information concerning particles at low latitudes is lost. Even when wave-particle observations occur locally, the cadence of the G-RBSP particle instruments is not designed to detect the characteristics of the interaction (other than the local pitch angle distribution). Unlike the forthcoming Russian mission RESONANCE (http://resonance.romance.iki.rssi.ru/) which has been designed to study wave-particle interactions by remaining on specific individual magnetic field lines mapping to specific ground observatories, the G-RBSP spacecraft cross magnetic fields lines in a mission designed to optimize the calculation of equatorial phase space density gradients from measurements by two spacecraft.

As a final comment, return to Figure 3 to consider the conditions most favorable for off-equatorial observations of wave emissions. According to the information presented in the figure, the greatest geomagnetic latitudes are attained at apogee during intervals when the instantaneous AOP is 90°. Consequently, the best observations of off-equatorial waves within the dayside magnetosphere will be made for an initial selection of AOP that cause the AOP to be ~90° when the apogees of the G-RBSP spacecraft pass through local noon.

Recommendation: Based on the need to make particle observations at equatorial latitudes to capture the full particle distribution and determine radial gradients in the phase space density, a requirement is recommended for a maximum 10° geographic latitude orbit inclination of with a goal of 6°.

2. Apogee: Orbits with distinctly different apogees of 5.5 and 5.8 R_E geocentric are preferable to those with identical apogees. If orbits with differing apogees are not possible, orbits with identical 5.8 R_E apogees are preferable to those with 5.5 or 5.2 R_E apogees.

The apogees of the G-RBSP spacecraft should be chosen to maximize coverage of a wide range of phenomena known to affect populations of relativistic and near-relativistic electrons and ions within the Earth's radiation belts. Regions of interest include the locations where particles are energized, transported, or lost by ULF and VLF waves, origin of the source populations, where they are injected into the radiation belts by substorm dipolarizations, and where their phase space densities peak and/or exhibit the greatest variability.

Several permutations of the original GMDT-recommended 5.5 R_E spacecraft apogee were considered to determine the optimal science return for the selected science investigations:

1) raise spacecraft apogee to 5.8 R_E.
2) lower spacecraft apogee to 5.2 R_E.
3) deploy the spacecraft into orbits with apogees separated by $\pm$0.3 R_E.

Discriminators between these possibilities include (A) whether the apogee is large enough to ensure observations of all relevant particle energization regions, (B) whether separating apogees enhances science return, (C) whether differential precession rates between the two spacecraft preclude intercomparison of observations, and (D) whether there are limits on the distances separating apogees. We conclude this section with a summary of the reasons for moving away from the GMDT-recommended pair of apogees at 5.5 R_E.

Consideration A: When the phenomena of interest exhibit limited radial extent or occur at rapidly increasing rates with increasing radial distance from Earth, the choice of apogee can play a critical role in determining the number of events observed. Figure 6 illustrates the spatial extent of several phenomena of great interest to the G-RBSP mission. The heart of the radiation belt, where fluxes peak, and regions of some wave activity (chorus, EMIC, magnetosonic) lie well within possible 5.2, 5.5, and 5.8 R_E apogees of the G-RBSP mission. The lower the apogee of the G-RBSP spacecraft, the more time would be spent in these regions. On the other, ULF wave activity, substorm dipolarizations, and source populations become increasingly prominent beyond 5 R_E, The further a spacecraft travels beyond 5 R_E, the greater its chances of observing these important phenomena.

Consequently, the strongest factor distinguishing missions with 5.5 (or 5.2) and 5.8 R_E apogees lies in the fact that G-RBSP is a mission of discovery and that the exact locations and spatial extents of the phenomena to be studied are not known. By selecting apogees of 5.8 R_E we err on the side of caution in achieving mission objectives: it is better to expand the radial coverage of the mission slightly than to confine it to lower altitudes and possibly miss important physics/phenomena.

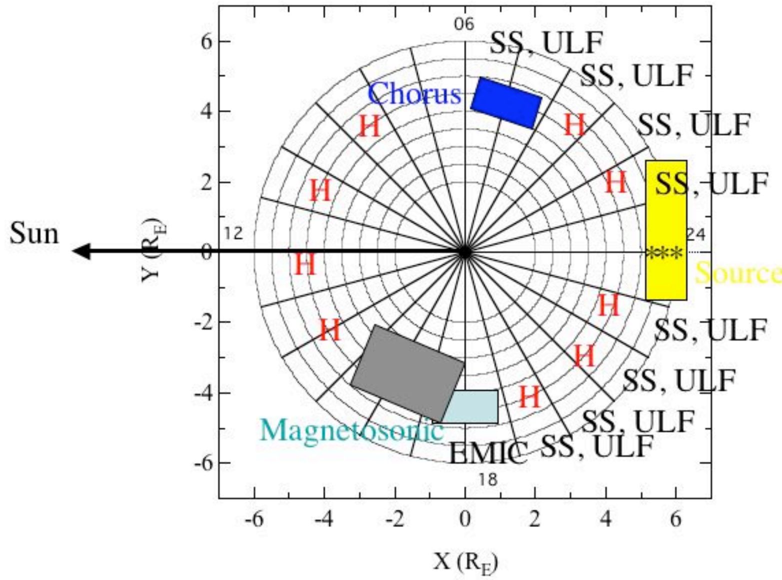

Figure 6. Some of the principle regions considered in the apogee analysis: Heart of the radiation belts, Substorm dipolarizations (SS), ultra low frequency waves (ULF), electromagnetic ion cyclotron waves (EMIC). Asterisks (in the yellow box) indicate 5.2, 5.5, and 5.8 R_E apogees for the RBSP spacecraft.

→**Consideration B:** Orbital configurations in which the apogees of the two nested spacecraft differ offer an opportunity to reduce risk related to meeting full mission success. Figure 7 shows histograms of L* occupancy for spacecraft with 5.2 R_E (green), 5.8 R_E (blue), and geosynchronous apogees (gray). The histograms of L* occupancy can be compared to the case study of *Iles et al* [2006], shown in the bottom panel of the same figure, in which the phase space density of energetic electrons is plotted as a function of L* over successive CRRES orbits during a geomagnetic storm.

The figure demonstrates why separating the apogees of the spacecraft offers three advantages. Separating the apogees (1) significantly increases the range of L* shells covered and therefore increases the likelihood that at least one spacecraft will be in the region of interest during the course of a radiation belt event, (2) significantly increases the fraction of the mission spent making instantaneous measurements of the radial phase space density gradients at locations where observations show considerable phase space density variability, and (3) compared to string of pearls scenarios in which the spacecraft are often closely separated increases the probability of observing orbit-by-orbit changes in phase space density over the entire range in radial distance covered by the spacecraft with the lower apogee.

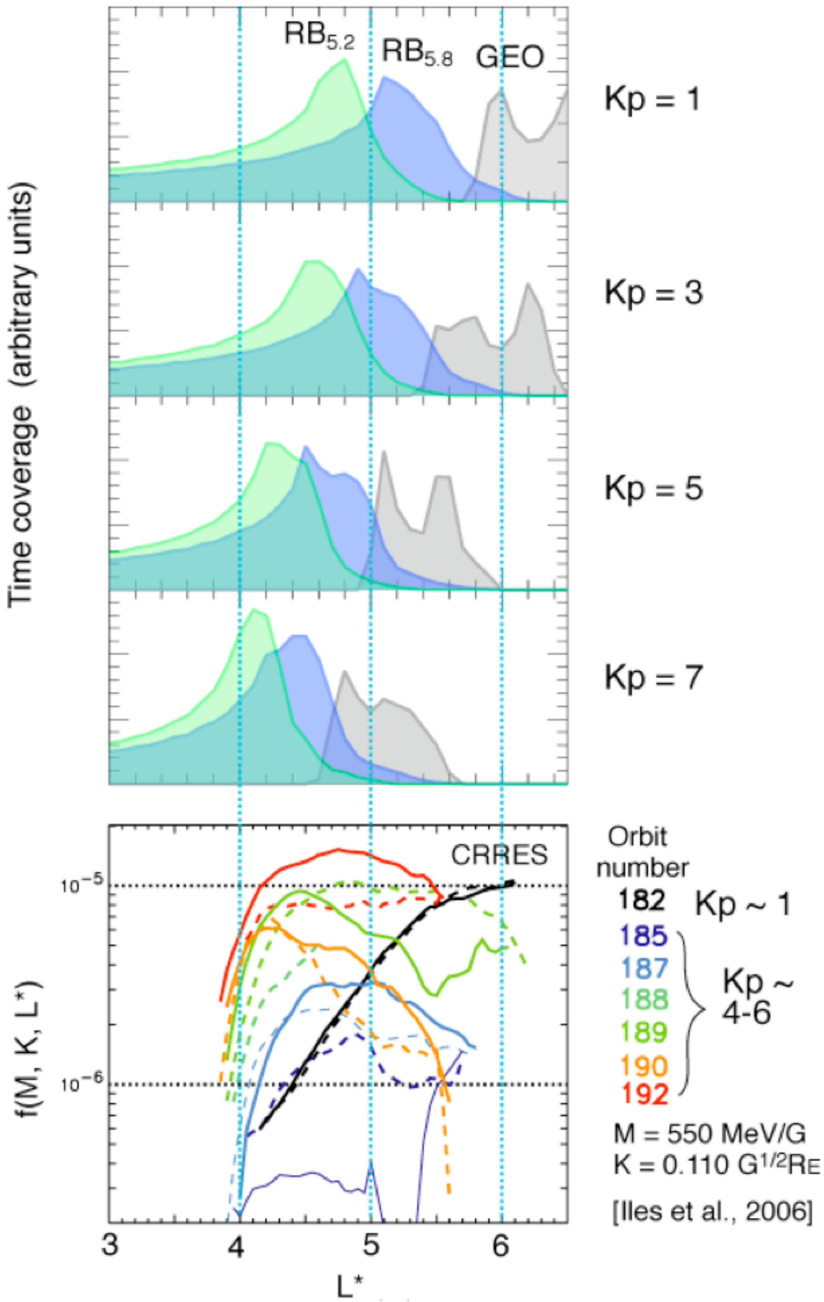

Figure 7. A comparison of the L* shells surveyed by G-RBSP spacecraft with apogees at 5.2 and 5.8 R_E during the course of a two-year mission with radial profiles for the phase space densities as a function of L*.

It is desirable to explore the full range of spatial scales inherent to radiation belt disturbances during the course of each disturbance, which typically is 305 days. Due to their long lapping rates, string of pearl missions do not do so. Figure 8 shows the L shells and magnetic local times covered by a string of pearl mission when the two spacecraft are closely-spaced. As illustrated in the second and fourth panels, throughout the course of a six-day interval, spacecraft separations in radius and local time remain small. Also, when the spacecraft are spaced far apart, separations remain large throughout entire events (not shown). As a result, the mission may fail to sample the full range of spatial scales inherent to rare, large, geomagnetic storms that occur once or twice during the mission. However, nested orbits also have potential disadvantages. As illustrated in Figure 9, nested orbits provide for separation distances that vary greatly over the course of individual storms, precluding systematic analysis of phenomena that occur on a fixed spatial or temporal scale.

The advantages of broadening the range of radial distances where the two spacecraft dwell, ensuring routine measurements of radial gradients, and ensuring that the two spacecraft routinely make more frequent radial passes than would a pair in closely-spaced string-of-pearls orbits, outweighs any difficulties associated irregular revisit times. Consequently, we recommend a pair of orbits with identical perigees and 5.5 and 5.8 R_E apogees.

Consideration C: The lines of apsides of spacecraft with differing apogees separate with time, and the rate of separation increases as the difference in apogees increases. This can be a benefit, as it enables identification of azimuthal structures and determination of their extent. While separations in longitude of 1-2 hours in local time pose little or no problem for direct intercomparison of instantaneous observations or successive passes through the radiation belts by two spacecraft, separations on the order of 4 hours rely more heavily on (not-necessarily) accurate magnetic field models. Figures 10 and 11 present the frequency of observations by two spacecraft with differing apogees at the end of a two-year mission as a function of their separation in radial distance and local time. Figure 10 shows that spacecraft with apogees at 5.8 and 5.5 R_E continue to make numerous observations at longitudinal separations of 1-2 hours in local time. By contrast, Figure 11 shows that spacecraft with apogees at 5.8 and 5.2 R_E make numerous observations at longitudinal separations separated by ~4 hr in local time. As the former configuration facilitates the comparisons required for primary mission objectives, apogees of 5.8 and 5.5 R_E are favored.

Note that a slow separation in the lines of apsides could also be obtained by displacing the perigees of one or both spacecraft while maintaining identical apogees. The feasibility, scope, and full science impact of the latter approach has not been studied but remains of interest.

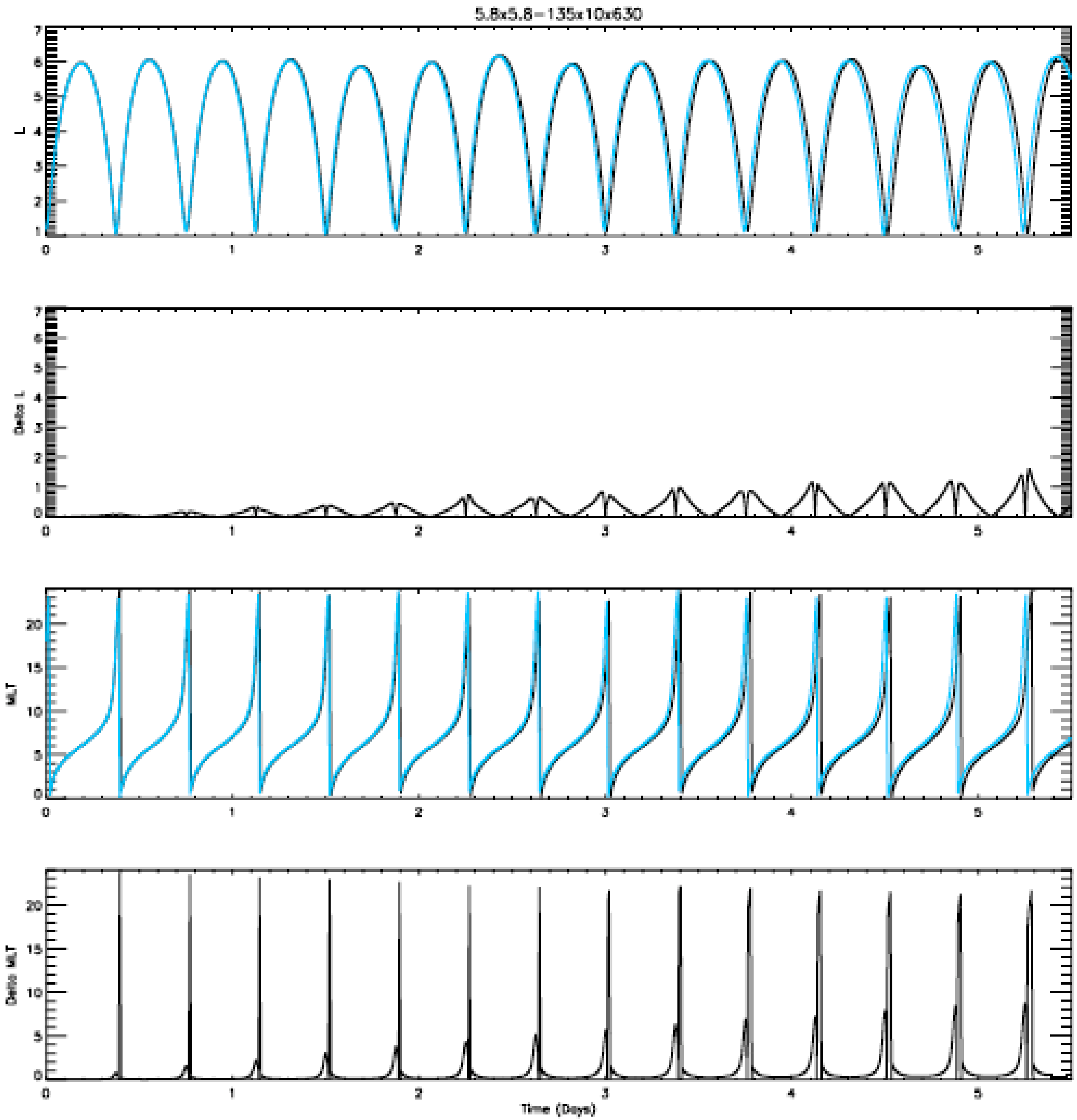

Figure 8. L shell (panel 1) and magnetic local time (panel 3) coverage for two closely-separated spacecraft in orbits with 5.8 R_E apogee over a 6 day period. Panels 2 and 4 depict the difference in L shells and MLT for the two spacecraft.

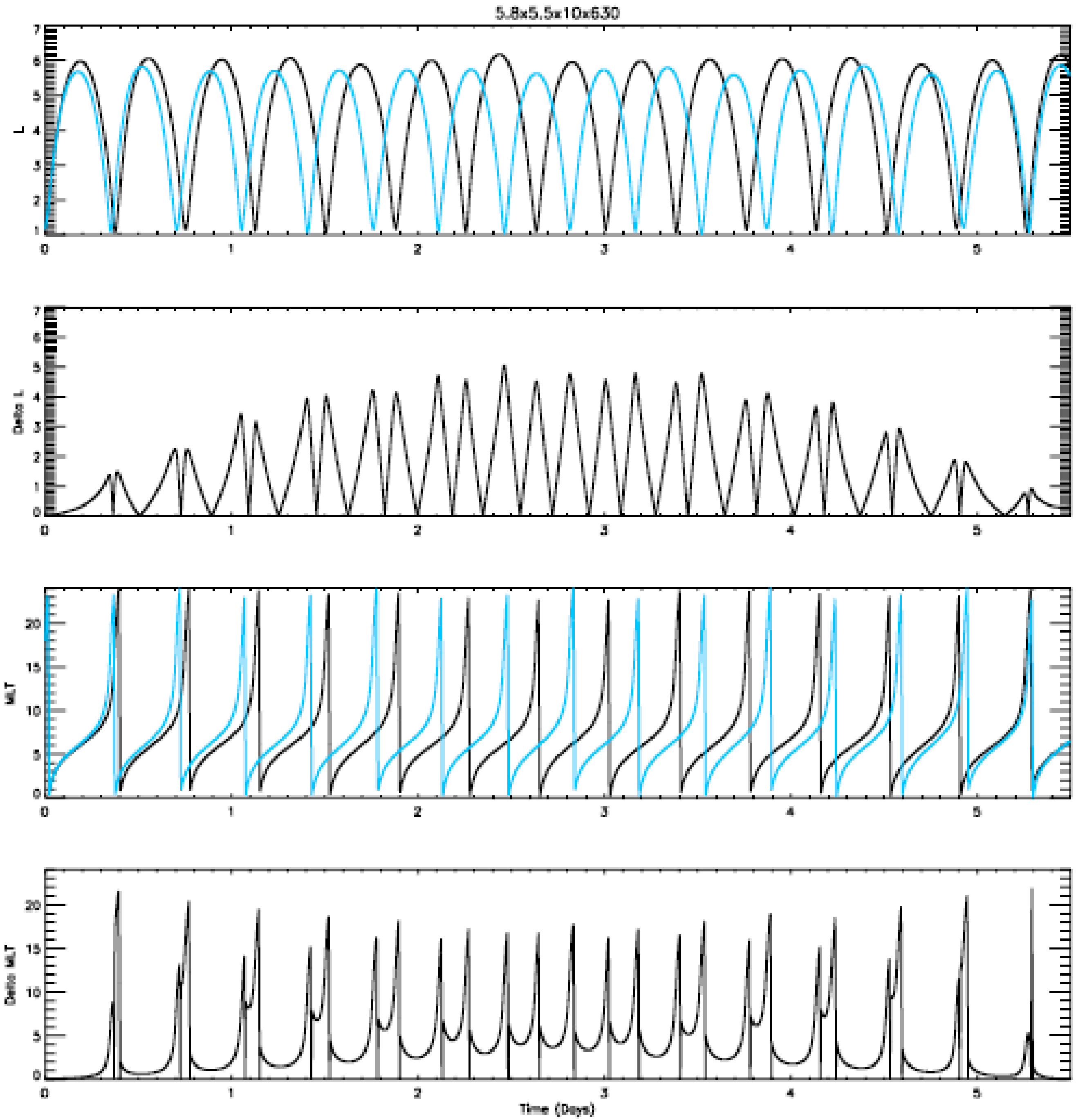

Figure 9. As in Figure 8, but for spacecraft with apogees at 5.5 and 5.8 R_E.

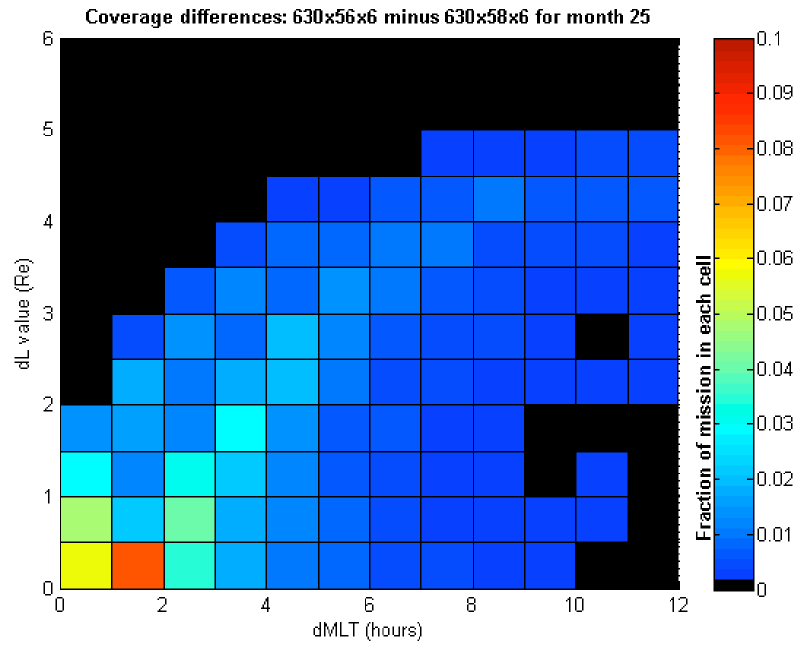

Figure 10. The distribution of distances and local times separating observations by two spacecraft with apogees at 5.5 and 5.8 R_E during the month following the end of the 2-year G-RBSP mission.

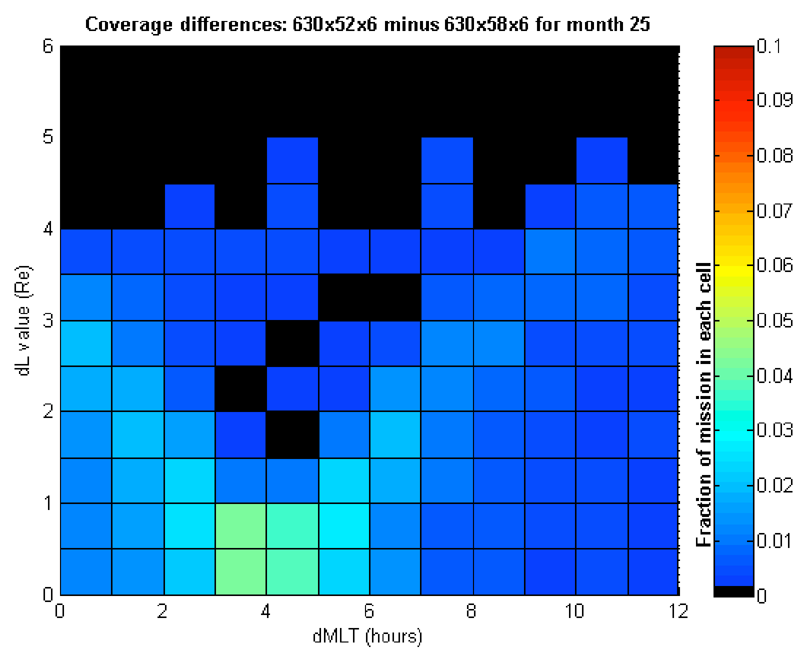

Figure 11. The distribution of distances and local times separating observations by two spacecraft with apogees at 5.2 and 5.8 R_E during the month following the end of the 2-year G-RBSP mission.

Consideration D: Apogee separations greater than 0.3 R_E are undesirable. Although maintaining the apogee of one spacecraft at 5.8 R_E and reducing the apogee of the second spacecraft to 5.2 R_E would (1) increase the time spent within the high flux region of the radiation belts, (2) enable studies of the longitudinal extent of various phenomena to occur earlier within the mission by increasing the rate at which the lines of apsides separate, and (3) provide for more rapid revisit times to locations within 5.2 R_E geocentric distance, it would also reduce opportunities to (1) determine the azimuthal structure of ULF wave fields in the region of interest beyond 5.2 R_E, (2) study source populations, (3) cross open drift paths from which particles are lost at the magnetopause, (4) encounter tail and ring current effects such as substorm dipolarizations, and (5) preclude calculation of local gradients in phase space density beyond 5.2 R_E. Reducing the apogees of the two spacecraft to 5.5 and 5.2 R_E would only exacerbate the latter concerns, while raising the prospect that important phenomena occurring at or beyond 5.5 R_E would be much less frequently observed.

Summary: The proposed orbital configuration represents a departure from the 5.5 and 5.5 R_E orbits recommended by the GMDT and the 5.8 and 5.8 R_E orbits stated in the AO. This change has occurred in response to several factors. The recognition that larger launch vehicles would be used, technical analysis indicating that the spacecraft propulsion systems would suffice to separate the apogees of the two spacecraft, a comprehensive statistical analysis of the relevant phenomena, a recognition that orbits with differing apogees routinely allow radial gradients in the phase space density to be measured within the radiation belts for extended periods of time, a recognition that azimuthal extents for various phenomena might be determined by allowing the lines of apsides to separate slowly, and the realization that the spatial extent of many phenomena remain to be determined all mitigate in favor of a pair of apogees at 5.5 and 5.8 $R_{E.}$

Recommendation: Based on a consideration of the issues described above a requirement is recommended for the apogees of the two spacecraft lie at 5.8 and 5.5 R_E. If such a separation cannot be obtained, the recommendation is for identical apogees at 5.8 R_E

ACKNOWLEDGEMENTS:

The analysis presented in this technical note is based on the deliberations of a tiger team led by D. Rowland and the teleconferences that they held from May to June 2007, orbital analysis by T. Sotirelis and G. Heyler, magnetic field mapping by K. Takahashi, extended discussions of LWS Geospace SWG team members and their designees during an in person meeting from June 26-27, 2007, and the final discussions of the RBSP Project Scientists.